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A method for calculating soil pressure overlying human burials

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ABSTRACT

While damage to the human skeleton due to vertical pressure exerted by overlying soil is a common observation at archaeological excavations, comparatively few studies have attempted to quantify the magnitude of this pressure. As part of a suite of taphonomic studies of a nineteenth-century cemetery located in Brisbane, Australia, a soil loading calculation equation usually employed in civil engineering is used to calculate soil vertical pressure at various depths for both child and adult graves. This cemetery was characterised by extreme vertical compression of coffin burials to the extent that human remains were sandwiched between the coffin base and lid to a thickness of just a few centimetres. Calculations determined that, because of their narrower grave shafts, the burials of children experienced between 40% (1.83 m depth) and 27% (0.91 m depth) less vertical soil pressure than those of adults buried at similar depths. Further calculations for different soil types showed that coarser grained soils such as gravel and sand exerted less vertical pressure than a similar volume of saturated clay due to the amount of air trapped between the coarser grains. It is anticipated that the equation utilised in this study could find widespread applications in the fields of archaeology, physical anthropology, forensic archaeology and cultural heritage management.

1. Introduction

The potential for vertical soil pressure to contribute to bone degradation was highlighted during a salvage excavation conducted at the North Brisbane Burial Ground (NBBG), a nineteenth-century cemetery in the centre of Brisbane, Queensland, Australia. Many of the burials had suffered damage due to extreme vertical compression (Fig. 1). In the majority of these the wooden coffin lid had fallen in and been pressed against the human remains and the coffin base. The sides of the coffins were deformed in response to soil movements, and had lost some of their vertical height, but still remained relatively upright (Fig. 2). Three wooden coffins with lead liners were generally more resistant to compression, with the sides showing inward buckling in response to vertical pressure (Fig. 3).

It is estimated that the NBBG received approximately 5000 interments between 1843 and 1875, in separate cemeteries according to religious denomination (Rains and Prangnell, 2002). The cemeteries were each located on dissected slopes of clay developed over phyllite bedrock (McGowan, 2008:197). Generally, bodies were buried in hexagonal wooden coffins covered inside and out with textiles (Prangnell and McGowan, 2013). There is contemporary documentary evidence that some burials were interred at quite shallow depths. In 1875, the Brisbane Courier (5/3/1875:2) reported that children's and adults' graves in the Anglican cemetery were only being dug to a depth of 3 ft (0.91 m), apparently upon instructions from the Trustees. After its closure, the Burial Ground became overgrown and neglected for a period of 36 years, before being redeveloped into parkland (Prangnell and McGowan, 2013). Low-lying parts were used as a municipal landfill and nightsoil disposal site from 1914 until the early 1960s (Prangnell and McGowan, 2009).

Earlier this century, the building of a new sports stadium on the site necessitated the excavation of 397 burials discovered during the preparation of foundations and service trenches (McGowan and Prangnell, 2011). Human remains, coffin wood, textiles and metal artefacts were found to be in a surprisingly poor state of preservation after only 160 years of burial, a comparatively brief time span by archaeological standards. By the time of excavation, 6% of coffin wood, 77% of textiles and 22% of metal coffin furniture had *completely disappeared* from the archaeological record (McGowan, 2008:364). Of the 397 burials excavated 54.2% contained only soil silhouettes, 29.9% contained highly compressed and powdered skeletons, 12.3% contained compressed and fragmented bones (Fig. 1), 3.4% had broken bones in anatomical position and one burial was well preserved with a complete but disarticulated skeleton (Fig. 3).

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Fig. 1. An example of extreme vertical compression typical of most graves at the North Brisbane Burial Ground (Head and torso of burial F15 in the Anglican cemetery). Many burials at North Brisbane were compressed to a vertical height of just a few centimetres. Segments on the scale bar are marked in 25 mm intervals.

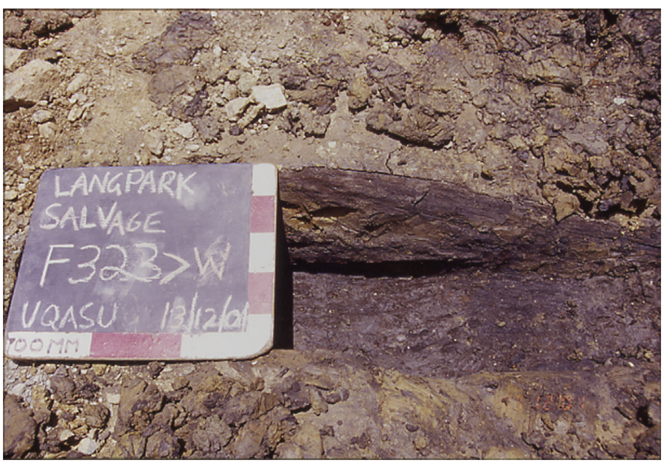

Fig. 2. Burial F323 in the Anglican cemetery showing the coffin lid compressed onto the base, with the sides deformed and shortened but still upright.

Fig. 3. Inward buckling and breakage of the wooden sides from lead lined coffin burial F206 in the Roman Catholic cemetery in response to vertical soil pressure.

It was noted that, in some places, burials were covered with overburden of more than 7 m of landfill waste (McGowan, 2008:212) (Fig. 4). Previous research into the taphonomic conditions at the North Brisbane Burial Ground has demonstrated that soil temperature (Prangnell and McGowan, 2009), soil pH (McGowan and Prangnell, 2006), fluctuating groundwater levels (McGowan, 2008), high soil salt content (McGowan, 2008), chemical attack from landfill leachate (McGowan, 2008) and ongoing microbial attack (McGowan and Prangnell, 2006) are factors involved in the degradation of human remains and artefacts at the site. Considering the extent of overburden and the heavily compressed nature of the remains a method of quantifying soil vertical pressure was also sought as part of this broad analysis of site taphonomy aimed at determining the critical factors leading to the extreme degradation observed.

2. Method

While there have been a multitude of studies published in the archaeological and forensic literature focussing upon the taphonomic effects of plant, animal, and microbial activity on human bone preservation, as well as the modifying effects of waterlogging and extreme heat, less attention has been devoted to the effects of soil physical and chemical parameters such as pH, chemical contamination, soil temperature and soil pressure. Crist et al. (1997) appear to be the only authors to attempt to quantify the weight of soil overburden on cemetery burials by modelling grave fill as a prism of earth sitting on the roof of the coffin and quantifying the weight of this soil prism based upon its volume. They calculated that for 4 ft (1.22 m) of soil cover in a grave shaft of dimensions 6 ft (1.83 m) by 3 ft (0.91 m), the volume of the grave infill would be approximately 72 ft^3 (2.03 m^3), and the total weight of this earth would be between 5,400 lb and 7,200 lb (2.45 and 3.27 tonne) based upon a unit weight of 75 lb (34.02 kg) to 100 lb (45.36 kg) per cubic foot of soil. However, engineering research conducted by Marston and associates found that the load on a buried linear object is not the same as the weight of the prism of earth above the object, and is in fact either greater or lesser than the weight of the fill itself, depending upon the rigidity of the buried object, the compactness of the soil and the method of trench construction and infilling (Liu, 2003:362–363).

A coffin is essentially a long narrow object buried in a trench which is also long and narrow-a situation similar to that of a buried pipeline. With this analogy in mind, a mathematical equation used in industry to calculate the pressure exerted by fill over buried pipelines was used to determine grave fill pressure in cemetery burials. The load on a conduit (or a coffin) is made up of the weight of the prism of earth fill above the top of the conduit pressing down, less the counteracting upward force of the total frictional or shear forces acting on the trench sides as the fill settles (Spangler and Handy, 1982:730). The degree of consolidation of the trench/grave fill is also important. When loose material is used to backfill the trench/grave, it settles downward under its own weight, while the surrounding rigid walls act to hold the fill

Fig. 4. Landfill refuse 7 m deep overlying the burial level (dark layer at the base of the section) in the Roman Catholic cemetery.

in place due to frictional shearing stress along the fill–wall interface. This leads to a transfer of load from the fill to the surrounding walls, with a subsequent reduction in the vertical pressure exerted on the conduit, an effect called "arching" (Dubé and Aubertin, 2013). Conversely, when the trench fill is purposely compacted, less settlement of the fill occurs and some of the load from the surrounding earth is transferred to the trench fill, causing greater loading than would be experienced from the weight of the overlying soil alone (called "reverse-arching" (Liu, 2003:363).

The equation chosen for the calculation of grave fill pressure is that of a *rigid pipe* buried in a *narrow trench* or *ditch conduit* where the pipeline is installed in a relatively narrow ditch dug in passive or undisturbed soil and then covered with earth backfill (Spangler and Handy, 1982:730). This equation may be used with metric (Spangler and Handy, 1982:732) or Imperial measurements (Clarke, 1968:26) and yields a force in the magnitude of Newtons per linear metre or pounds per linear foot respectively. The elements of the equation are depicted in Fig. 5.

The initial equation for the calculation of fill load is (Spangler and Handy, 1982:732):

$$V + \mathrm{d}V + 2K\mu'\frac{V}{B_d}\mathrm{d}h = V + \gamma B_d \mathrm{d}h$$

This is essentially the same equation published earlier by Clarke for use with Imperial measurements (1968:26).

$$V + \mathrm{d}V = V + \gamma B_d \mathrm{d}h - 2K\mu'\frac{V}{B_d}\mathrm{d}h$$

Where:

V is the vertical load on any horizontal plane in backfill (ie. the load on an element of fill at depth h in the fill prism), in N/linear m or lb/linear ft

γ is the unit weight (saturated density) of soil fill, in N/m^3 or lb/ft^3

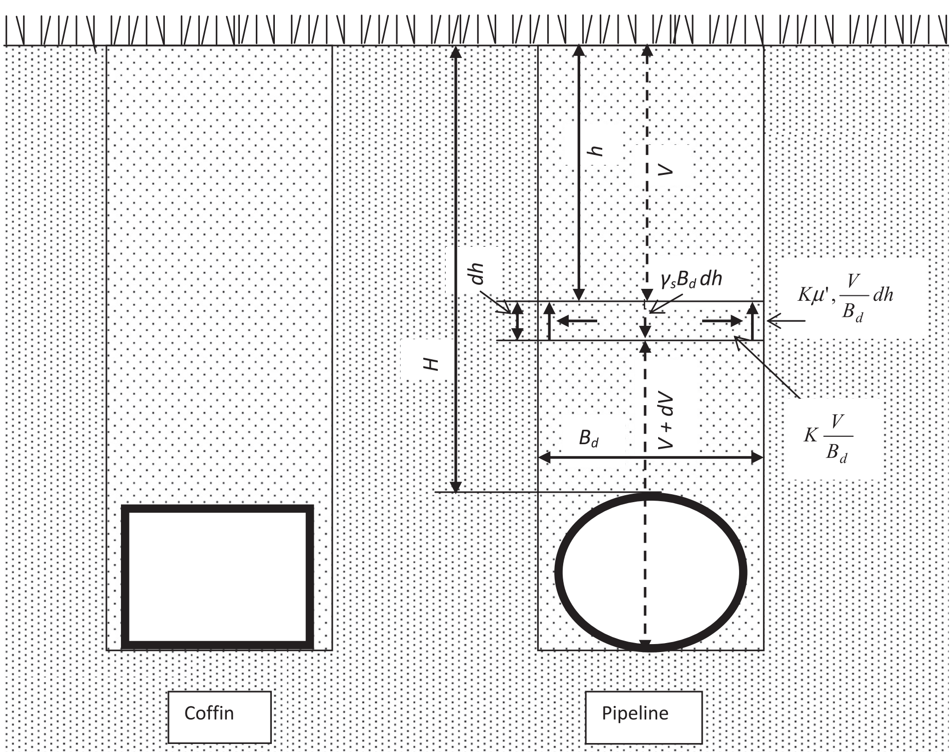

Fig. 5. Comparison of a buried pipeline and a cemetery coffin burial. The elements required for the calculation of fill load on a buried pipeline are shown on the right of the diagram. (After Clarke 1968:26, Fig. 4.1).

B_d is the horizontal width of the trench at the top of the conduit (also called the "effective width"), in m or ft
h is the distance from the ground surface down to any horizontal plane in backfill, in m or ft
K is Rankine's coefficient of lateral earth pressure ie. the ratio of active lateral unit pressure to vertical unit pressure, dimensionless
μ' is the coefficient of sliding friction of fill on the undisturbed soil of the trench sides, dimensionless
H is the height of fill above the top of the conduit, in m or ft

The solution of the differential equation above is (Spangler and Handy, 1982:732):

$$V = \gamma B_d^2 \left(\frac{1 - e^{-2K\mu' h/B_d}}{2K\mu'} \right)$$

When $h = H$, then the total load on the conduit is (Clarke, 1968:26):

$$W_C = \gamma_s B_d^2 \left(\frac{1 - e^{-2K\mu' h/B_d}}{2K\mu'} \right)$$

Where

W_c is the magnitude of load caused by fill in a narrow trench situation, in N/linear m or lb/linear ft

The five values that Clarke (1968:245, Chart C1), provides of $K\mu'$ depend upon soil type (Table 2).

The value γ (the saturated density of soil) was taken as 120 lb/ft^3 (18 838 N/m^3) from Clarke (1968:267). Unless specific laboratory testing for the saturated density of a particular soil has been conducted it is industry convention that the saturated density of the soil is taken to be 120 lb/ft^3 (Liu, 2003:365).

For cemetery burials, the value for H is the depth of the burial shaft minus the height of the coffin. Since the coffins excavated at the NBBG were greatly compressed, an accurate measurement of original coffin height was impossible. However, Higginbotham (2002) in his excavation of Cadia Cemetery in western New South Wales which received interments between 1864 and 1927, measured a coffin height of 13–20 cm for children and 20–30 cm for adults. Therefore, the maximum heights were used for calculations: 0.65 ft (20 cm) for children and 0.98 ft (30 cm) for adults.

For adult burials, the dimension for B_d (the width of the trench at the top of the conduit), was taken as 3 ft (0.91 m), since the maximum measured width of adult NBBG coffins was 63.5 cm and at Cadia Cemetery it was 60 cm (Higginbotham, 2002). For the burials of children, B_d was taken as 2 ft (0.61 m), based on a maximum coffin width of 30 cm. At the NBBG, the maximum width of children's coffins was 38.5 cm, while at Cadia Cemetery, the width of children's coffins was 20 cm. A width of 30 cm for children's coffins was considered an appropriate estimate as many of the North Brisbane coffins had suffered deformation of the coffin walls which could have distorted coffin width measurements.

Table 2
Values $K\mu'$ dependent upon soil type from Clarke 1968:245, Chart C1.

Type of soil fill	Value for $K\mu'$
Saturated clay	0.110
Clay	0.130
Saturated soil	0.150
Sand and gravel	0.165
Granular materials without cohesion (gravel)	0.19

3. Calculations

This study calculated soil vertical pressure for six different situations that existed at the NBBG site:

Example 1. An Adult burial at a traditional depth of 6 ft (1.83 m)
In this example H = 5 ft (1.52 m) as an adult coffin in the base of a grave shaft is taken as being 30 cm high.

Example 2. A Child burial at a traditional depth of 6 ft (1.83 m)
In this example H = 5.33 ft (1.63 m) because a coffin in the base of a grave shaft is taken as being 20 cm high.

Example 3. An Adult burial at a shallow depth of 3 ft (0.91 m)
This calculation, along with that in Example 4, simulates shallow burial at 3 ft depth, since this was said to have occurred at the NBBG. For adult burials, H = 2 ft (0.61 m).

Example 4. A Child burial at a shallow depth of 3 ft (0.91 m)
For a child's burial made at 3 ft depth, H = 2.33 ft (0.71 m).

Example 5. An Adult burial at a depth of 12 ft (3.66 m)
This calculation approximates the loading applied to in situ graves following the addition of a thick layer of landfill refuse to the original ground surface. A buried coffin can be modelled as having an extremely tall prism of earth over it, made up of the original grave fill, plus a column of landfill above. The figure of 3.66 m was arbitrarily selected, being twice the traditional depth of burial. For an adult coffin 1 ft (0.31 m) high, this makes the value for H in the calculation 11 ft (3.35 m). For simplicity, the density figure (γ) was kept the same for landfill refuse as well as soil. It is important to note that this calculation is less precise than those for Examples 1 to 4 because the value for $K\mu'$ in the prism of landfill refuse will vary hugely depending upon the local grain size of the rubbish, which

Table 1
Calculated vertical soil pressure in Metric and Imperial units for adults' and children's graves buried at different depths and in different soil types.

		Saturated clay	Clay	Saturated soil	Sand & gravel	Gravel
Example 1- Adult at 6 ft (1.83 m)	lb/lin ft	1506.9	1460.7	1416.5	1384.5	1333.5
	N/lin m	21,290	20,638	20,012	19,561	18,840
Example 2- Child at 6 ft (1.83 m)	lb/lin ft	968.3	923.2	881	851.2	804.6
	N/lin m	14,115	13,458	12,844	12,409	11,730
Example 3- Adult at 3 ft (0.91 m)	lb/lin ft	669.7	661.1	652.6	646.3	636
	N/lin m	9461	9340	9220	9131	8986
Example 4- Child at 3 ft (0.91 m)	lb/lin ft	493.8	483	472.4	464.7	452.3
	N/lin m	7201	7043	6889	6777	6595
Example 5- Adult at 12 ft (3.66 m)	lb/lin ft	2717.9	2552.7	2401.7	2296.8	2136.6
	N/lin m	38,401	36,066	33,932	32,450	30,186
Example 6- Adult at 29 ft (8.84 m)	lb/lin ft	4346.1	3832.5	3412.1	3145.6	2774.6
	N/lin m	61,088	53,934	48,064	44,335	39,135

could be anything from silt or clay size (eg. dumped ashes) to gravel size or larger (eg. dumped cans or bottles).

Example 6. An Adult burial at a depth of 29 ft (8.84)m

This calculation approximates the maximum loading on adult coffins as seen in parts of the Roman Catholic cemetery at the NBBG. At excavation, it was found that this area of the Burial Ground was covered by over 7 m of landfill refuse and soil fill. As in Example 5, it is impossible to accurately calculate the total loading due to the irregular grain size of the landfill rubbish. The value for H in the calculation was 28 ft (8.53 m).

It is important to note that all of these examples are for non-waterlogged burials. As noted by Liu (2003:370), when a pipeline is installed in an area of high or fluctuating groundwater, it is not sufficient just to calculate the loading associated with vertical soil pressure; the load generated by water table fluctuations must also be taken into consideration. The calculation of groundwater loading is outside the scope of the present study, and will be considered in a further study.

The results of calculations made for each of the six examples (in both metric and imperial measurements) are shown in Table 1. While these results are more accurate than figures for soil vertical pressure arrived at by just calculating the weight of the overlying soil prism on its own, it is expected that the soil weight loading in cemeteries would be slightly different to the soil weight loading experienced by a pipeline of similar dimensions and burial depth to a coffin. This is because pipeline trenches are essentially infinite in length, while a grave cut has not only sides, but head and foot ends as well. It is anticipated that frictional shear forces that act at the fill-wall interface on the sides of the burial pit would also act at the fill-wall interfaces at the head and foot of the burial pit, having the net result of producing slightly less vertical loading than has been calculated here using an equation specific for pipeline installations.

4. Results

It can be seen from Example 1 that the force applied to a buried adult coffin by the weight of grave fill varies from a minimum of 18,840 N/lin m (1333.46 lb/lin ft) for gravel fill to a maximum of 21,290 N/lin m (1506.89 lb/lin ft) for saturated clay fill. With larger grain sizes in the fill, more air is incorporated into the soil block, making the overall mass (and therefore the force applied) less. In the case of the NBBG, calculations for saturated clay, clay and saturated soil types are the most applicable, since this more closely approximates the original soil profile at North Brisbane.

A comparison of the soil loading pressure calculated for adult burials and children's burials made at the same depth (Examples 1 and 2, and 3 and 4) shows that children's burials would experience less soil pressure. This is because the grave shaft dug for children is narrower than that dug for adults, making the overall mass of the fill less. In addition, the fill–soil interface is larger than that of adult burials, because the smaller height of the child's coffin creates a larger space for frictional shear forces to operate and potentially counteract some of the downward soil pressure. The calculations show that the burials of children would experience between 40% (6 ft) and 27% (3 ft) less vertical soil pressure than those of adults buried at similar depths. In addition, the force exerted by grave fill on an adult sized burial at the shallow depth of 3 ft would be less than the force exerted on a child sized burial at the traditional depth of 6 ft.

Examples 5 and 6 approximate the successive vertical loading that would have occurred during landfill dumping at the site over a period of approximately 46 years as the waste pile gradually became thicker. The heterogeneity of landfill waste makes it difficult to arrive at an exact figure for the density of the landfill layers, making these calculations of soil vertical loading less accurate than in Examples 1–4. Example 6 simulates the maximum loading on adult coffins as was seen in parts of the Roman Catholic cemetery at the NBBG. At excavation, it was found that this area of the Burial Ground was covered by over 7 m (22.96 ft) of landfill refuse and soil fill. The calculated values for soil pressure represent the greatest loading experienced by coffins at the NBBG, since the coffins of children consistently experience less loading due to the smaller width of their grave shafts.

Vertical soil pressure acting upon graves at the NBBG changed in magnitude over the 160 years of interment. Once the coffin was deposited the grave pit would have been backfilled with soil of variable grain size, being a random mixture of the surface soil, as well as the subsurface clay. This irregular grain size distribution, combined with the lack of consolidation would have incorporated air into the grave fill, thus producing a magnitude of soil weight loading less than that experienced by a burial under compacted grave fill.

During the period 1843 to 1913, when the original ground surface was still intact, our calculations indicate that adult interments at the NBBG would have been subjected to between 653 and 670 lb/lin ft (9220–9461 N/lin m) of soil vertical pressure for burials at 3 ft depth, depending upon the grain size of the soil and its water content. For interments made at 6 ft depth, adult burials would have experienced between 1416 and 1507 lb/lin ft (20,012–21,290 N/lin m) of soil pressure, depending upon local soil conditions.

Once the dumping of municipal and light industrial waste began from 1914 onwards, and a succession of sporting facilities were built, the cemetery remains would have experienced ever greater weight loading. The maximum vertical soil pressure was experienced by Roman Catholic graves at the NBBG where an overburden of 7 m of refuse and imported fill generated pressures of between 3381 and 4279 lb/lin ft (48,064–61,088 N/lin m). These calculations have demonstrated that in some areas of the NBBG, graves experienced a vertical soil pressure two to three times greater than the pressure experienced in an undisturbed inhumation cemetery (compare Examples 1 and 6). The degree of mechanical damage inflicted upon the burial assemblage due to this pressure must have been extreme and undoubtedly contributed greatly to the poor preservation of human remains, coffin wood and pressed metal decorations noted at the time of excavation.

5. Discussion

It is evident from this analysis that human remains and funerary artefacts interred at the North Brisbane Burial Ground experienced extreme vertical loading. Rubbish dumping proceeded for almost 50 years in various parts of the site, with some areas receiving over 7 m of landfill. This site probably exemplifies the absolute limit of vertical weight loading beyond which human burials cease to exist in the archaeological record (ie the point of total destruction). More particularly, this study highlights important differences in soil pressure arising from the difference in grave cut dimensions for child and adult burials. The burials of children experience between 40% (1.83 m depth) and 27% (0.91 m depth) less vertical soil pressure than those of adults buried at similar depths. As expected, soil vertical pressure increased with increasing depth of burial, and with decreasing grain size of the fill material. Calculations made for a variety of soil types show that air trapped between the grains in gravel and sand grave fill has the effect of decreasing the overall weight load on the coffin, in comparison to very fine grained waterlogged grave fill which admits no air and presents a solid mass lying directly over the coffin.

The grain size of the grave fill and cemetery soil in general is also a major determining factor on the amount of soft tissue remaining to cushion the bones at the time of coffin collapse. At the NBBG, interments made in clay or waterlogged clay may well have retained significant amounts of soft tissue for up to 40 years post-interment (see Lotterle et al. 1982; Schutzenmeister, 1972), thus providing some protection to the bones when the coffin failed. However, once landscaping and rubbish dumping began at the burial ground in 1914, some 39 years after the last interment, it is not expected that sufficient soft tissue remained to protect skeletal elements from the extra weight loading applied by the landfill material.

Voids between grains in the grave fill will decrease in number and size as the grave fill compacts. When the grave is initially infilled with a random mixture of topsoil and subsoil, the irregular grain size distribution and air pockets between grains exert less vertical pressure than would be expected from compacted grave fill of the same mineral composition. The irregular grain size distribution and increased porosity due to a lack of consolidation also disrupts the normal soil drainage pattern around the grave site, attracting moisture into the grave (the "sponge effect" described by Dent and Knight (1998)). This moisture may contribute to the weakening of the coffin lid through hydrolysis of hemicellulose in the wood (Hoffmann and Jones, 1990), and may gradually increase the weight loading as water replaces air in the grave fill voids. Over time, the grave fill becomes fully consolidated and the vertical weight loading remains more or less constant.

The shape of the coffin may have a significant influence upon the amount of vertical weight loading experienced by the encoffined body as a whole, and by different parts of the skeleton. A burial within a hexagonal coffin which has its widest point at the shoulders, and tapers at the head and feet would experience greatest coffin stress at the level of the shoulders where the coffin lid acts like a beam spanning the widest part of the coffin. At the head, and particularly at the foot of the coffin, the distance to be spanned by the lid is considerably less, and these areas would be able to withstand vertical weight loading to a greater extent than at the shoulders. At the NBBG excavation, the failure of the coffin at the point of the shoulders, with the coffin lid pressed down onto the coffin base and the sides remaining *in situ* was a common finding (Fig. 2).

This method provides a means of quantifying the magnitude of soil pressure acting upon any individual burial, so that this effect can be evaluated against other phenomena operating within the environment of that particular interment. The discipline of Field Anthropology (previously known as "*l'Anthropologie de Terrain*") was pioneered in France in the 1970s and uses the meticulous identification and recording of the spatial relationships of bones within a grave to interpret the process of body decomposition and reconstruct the original burial context at the time the body was deposited (Willis and Tayles, 2009). Using these techniques, it is often possible to determine whether the position of the skeletal elements in the grave is due primarily to the natural process of decomposition or to cultural behaviours related to the interment and conducted at the time of burial (eg. Ortiz et al. 2013). In addition to the sequence of disarticulation of the skeletal elements, physical factors such as the presence or absence of a burial container, the effect of gravity on bone movement and the effects of vertical and lateral soil pressure are assessed (Duday and Guillon, 2006). It would be of considerable advantage to be able to place a quantitative estimate of soil vertical pressure within this overall analysis. However, the method of vertical soil pressure used in this study is most applicable to cemetery burials where grave cuts have more-or-less vertical sides. For burials made in pits with sloping sides, it would be more appropriate to utilise the extension to Marston's solution offered by Dubé and Aubertin (2013) for back-filled trenches with inclined walls.

In contrast to cemetery burials, clandestine burials examined during forensic investigations often occur at shallower depths. A recent review of clandestine burials discovered between 1993 and 2003 in the Unites States found that the depth of burial ranged between 46 cm and 76 cm (1.5–2.5 ft) (Hoffman et al. 2009). While this is not associated with excessive soil weight loading, a smaller number of clandestine burials are discovered at greater depths where soil weight loading may be an important taphonomic factor. In rare cases of burial under concrete slabs (eg. Toms et al. 2008), the ability to calculate vertical weight loading would allow interpretations to be made as to the extent to which observed damage to bones and personal effects was the result of excessive soil pressure or the actions of a perpetrator. The ability to scientifically quantify the magnitude of vertical soil pressure exerted on human remains and personal effects has obvious benefits fir crime scene investigation and the presenting of evidence at legal proceedings.

There are non-cemetery archaeological applications of this method including for the analysis of vertical soil pressure acting on other features with vertical (or near vertical) sides, such as foundation trenches, cisterns, ditches, storage bins, and the infill of architectural features where the walls remain wholly or partly *in situ*. The quantification of soil weight loading within vertically walled structures may also help in stratigraphic interpretation. de Lange et al. (2012) have speculated that the compression of weak layers within the soil profile, such as unconsolidated clay or peat, could cause deformation and buckling of these layers such that the original context and association of artefacts within them would be significantly altered and site interpretation impaired. An awareness of the magnitude of soil vertical pressure would assist in the understanding of this phenomenon. It is important to note, however, that this method of calculation is not applicable in the case of objects left on an old ground surface and subsequently covered over with successive strata. In these instances, the buried object fills the criteria for a "positive projecting conduit", where a pipe (or object) is installed in shallow bedding with the top of the pipe projecting above the natural ground level, and then covered over with earth to form an embankment (Liu, 2003:363). Under these circumstances, the most appropriate method of calculating soil vertical pressure is that employed by Spangler and Handy (1982:739–748) for positive projection situations.

6. Conclusion

This study marks the first occasion in which a mathematical formula normally used in civil engineering applications has been used to calculate vertical soil pressure at a historic cemetery site. The calculated vertical soil pressure for the North Brisbane Burial Ground demonstrates important differences in soil pressure arising from the difference in grave cut dimensions for child and adult burials. The burials of children experience up to 40% less vertical soil pressure than those of adults buried at similar depths. As expected, soil vertical pressure increases with increasing depth of burial. Calculations made for a variety of soil types show that air trapped between the grains in gravel and sand grave fill has the effect of decreasing the overall weight load on the coffin, in comparison to very fine grained waterlogged grave fill which admits no air and presents a solid mass lying directly over the coffin.

Damage to human bones as a result of exposure to excessive vertical soil pressure is a common observation during the archaeological excavation of burials. It is anticipated that the equation utilised in this study could find widespread applications in the fields of archaeology, field anthropology, forensic archaeology and forensic anthropology. The ability to scientifically quantify the

magnitude of soil vertical pressure also has the potential to greatly enhance the information available to cultural heritage managers considering the option of *in situ* preservation for historic cemetery sites.

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References

Brisbane Courier, March 5th, 1875:2.

Clarke, N., 1968. Buried Pipelines: a Manual of Structural Design and Installation. Maclaren and Sons, London.

Crist, T., Washburn, A., Park, H., Hood, I., Hickey, M., 1997. Cranial bone displacement as a taphonomic process in potential child abuse cases. In: Haglund, W., Sorg, M. (Eds.), Forensic Taphonomy: the Postmortem Fate of Human Remains. CRC Press, Boca Raton, pp. 319–335.

de Lange, G., Gakr, M., Gunnink, J., Huisman, D., 2012. A predictive map of compression- sensitivity of the Dutch archaeological soil archive. Conserv. Manag. Archaeol. Sites 14 (1–4), 284–293.

Dent, B., Knight, M., 1998. Cemeteries: a Special Kind of Landfill. The Context of Their Sustainable Management. In: Groundwater: Sustainable Solutions, pp. 451–456. Melbourne: Conference of the International Association of Hydrogeologists, 8-13 February 1998.

Dubé, J.-S., Aubertin, M., 2013. An extension of Marston's solution for the stresses in backfilled trenches with inclined walls. Geotech. Geol. Eng. 31, 1027–1039.

Duday, H., Guillon, M., 2006. Understanding the circumstances of decomposition when the body is skeletonized. In: Schmitt, A., Cunha, E., Pinheiro, J. (Eds.), Forensic Anthropology and Medicine: Complementary Sciences from Recovery to Cause of Death. Humana Press Inc, Totowa, New Jersey, pp. 117–157.

Higginbotham, E., 2002. Report on the Excavation of the Cadia Cemetery, Cadia Road, Cadia, N.S.W. 1997-1998. Volume 1- Main Report. Edward Higginbotham & Associates Pty Ltd, Haberfield, NSW (Unpublished report for Cadia Holdings Pty Ltd).

Hoffman, E., Curran, A., Dulgerian, N., Stockham, R., Eckenrode, B., 2009. Characterization of the volatile organic compounds present in the headspace of decomposing human remains. Forensic Sci. Int. 186, 6–13.

Hoffmann, P., Jones, M., 1990. Structure and degradation process of waterlogged archaeological Wood. In: Rowell, R., Barbour, R. (Eds.), Archaeological Wood: Properties, Chemistry and Preservation, Advances in Chemistry Series No. 25. American Chemical Society, Washington DC, pp. 36–65.

Liu, H., 2003. Pipeline Engineering. CRC Press LLC, Boca Raton, Florida.

Lotterle, V., Schmierl, G., Schellmann, B., 1982. Einfluß der Bodenart auf die Leichendekomposition bei langen Liegezeiten. Beitr. zur gerichtl. Med. 40, 197–201.

McGowan, G., 2008. The Deterioration of Human Remains and Artefacts in the Cemetery Environment: a Study of Archaeological Materials Excavated from the Nineteenth Century North Brisbane Burial Ground, Lang Park, Queensland. Unpublished PhD thesis. The University of Queensland, Brisbane.

McGowan, G., Prangnell, J., 2006. The significance of vivianite in archaeological settings. Geoarchaeology 21, 93–111.

McGowan, G., Prangnell, J., 2011. Nineteenth century buttons from the North Brisbane burial ground. Australas. Hist. Archaeol. 29, 13–23.

Ortiz, A., Chambon, P., Molist, M., 2013. "Funerary bundles" in the PPNB at the archaeological site of Tell Halula (middle Euphrates valley, Syria): analysis of the taphonomic dynamics of seated bodies. J. Archaeol. Sci. 40, 4150–4161.

Prangnell, J., McGowan, G., 2009. Soil temperature calculation for burial site analysis. Forensic Sci. Int. 191, 104–109.

Prangnell, J., McGowan, G., 2013. Economy and respectability: textiles from the North Brisbane burial ground. Int. J. Hist. Archaeol. 17, 487–519.

Rains, K., Prangnell, J., 2002. Background to the University of Queensland Archaeological Services Unit's Lang Park salvage excavations: history, significance, assessment and methods. Qld. Archaeol. Res. 13, 21–30.

Schutzenmeister, W., 1972. Die geologischen Bedingungen für Friedhofsstandorte. Z. fur Gesamte Hyg. ihre Grenzgeb. 18 (2), 87–90.

Spangler, M., Handy, R., 1982. Soil Engineering, fourth ed. Harper & Row Publishers, New York.

Toms, C., Rogers, C., Sathyavagiswaran, L., 2008. Investigation of homicides interred in concrete: the Los Angeles experience. J. Forensic Sci. 53, 203–207.

Willis, A., Tayles, N., 2009. Field Anthropology: application to burial contexts in prehistoric Southeast Asia. J. Archaeol. Sci. 36, 547–554.